

Probing supernova ejecta by $H\alpha$ damping wings

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ABSTRACT

It is predicted that the $H\alpha$ emission line at the early nebular epoch of type II-P supernovae may display robust observational effects of radiation damping wings. Monte Carlo simulations demonstrate that the $H\alpha$ line with the optical depth typical of the early nebular epoch acquires extended wings and redshift and becomes broader compared to the Sobolev approximation case. The strength of these effects may be used for constraining parameters of the line-emitting zone. The anomalous redshift, width and red wing of the $H\alpha$ emission in the supernova SN 1997D on day 150 are explained in terms of damping wings effects.

Subject headings: line: profile, formation — supernovae: individual (SN 1997D)

1. Introduction

The ejecta structure of a type II-P supernova (SN II-P) may be sketchy portrayed as a combination of a hydrogen envelope and a "mixed core". The latter, being a macroscopic mixture of newly synthesised elements, such as, He, O, ^{56}Ni with a fraction of the hydrogen envelope, is responsible for the luminosity at the nebular epoch, i.e., at the age > 100 d. The model of mixed core of SN II-P is fundamental to the assesment of the nucleosynthesis yields, which is the subject of great interest. Two recent nebular models of SN 1987A (De Kool, Li & McCray 1998; Kozma & Fransson 1998) demonstrate that the basic physical processes in the mixed core are well understood to make feasible the composition analysis. However, to achieve this goal a nebular model of SN II-P should, first, pass the rigorous test on reproducing fluxes and profiles of hydrogen lines, including $\text{H}\alpha$.

Here I argue that the model of the $\text{H}\alpha$ line in SN II-P at the early nebular epoch (100–200 d after the outburst) should essentially include effects of radiation damping wings always ignored before. The physical reason for the damping wings to play a role is a high degree of a non-thermal excitation of hydrogen in the mixed core of SN II-P, which results in the large $\text{H}\alpha$ optical depth at the early nebular epoch. In this situation to model $\text{H}\alpha$ damping wing effects the Sobolev (local escape) approximation must be abandoned. The radiation transfer in the physical and the frequency space simulated with the Monte Carlo method is applied to demonstrate expected effects of the $\text{H}\alpha$ damping wings in SN II-P (Section 2). Recently found in SN 1997D a disparity between the large asymmetry of $\text{H}\alpha$ at the early nebular phase and the symmetric $\text{H}\alpha$ profile at the late nebular epoch (Chugai & Utrobin 1999) admits a simple explanation in terms of the damping wings (Section 3). Another motivation to address the issue of the $\text{H}\alpha$ damping wings in SN II-P is that this factor may provide an independent diagnostic tool for constraining parameters of the mixed core.

2. Expected effects of $\text{H}\alpha$ damping wings in SN II-P

The Sobolev approximation widely used to analyse supernova optical spectra is justified for most lines because of a highly supersonic expansion, $v/u \gg 1$, (v and u being the expansion and the thermal velocity, respectively). However, if the optical depth

in damping wings is large, the "supersonic" criterion for the local escape of photons should be replaced by the inequality $v/u \gg a\tau$ (Chugai 1980), where a is the Voigt parameter, $\tau = k\lambda t$ is the Sobolev optical depth (k is the line integrated absorption coefficient, λ is the wavelength, t is the expansion time). The $\text{H}\alpha$ Voigt parameter is $a = (A_{32} + A_{31} + A_{21})/(4\pi\Delta\nu_D) = 3.27 \times 10^{-3}$, where A_{ik} is the Einstein transition probability, $\Delta\nu_D$ is the thermal Doppler width (kinetic temperature of 5000 K is adopted). At the early nebular epoch (~ 150 d) the Sobolev optical depth of the mixed core in $\text{H}\alpha$ may exceed 10^5 (Xu et al. 1992) implying that $v/u \sim 2 \times 10^2$, i.e., is of the order of $a\tau$. In this case the local escape approximation is too crude, so that the full radiation transfer should be applied to compute the $\text{H}\alpha$ line profile.

One needs, first, to specify the frequency redistribution function for the $\text{H}\alpha$ damping wings. Let x' and x be the incident and scattered photon frequencies in the atom frame. With lower and upper levels broadened by the radiation damping, the atomic angle-averaged frequency redistribution function in far wings ($|x'| \gg a$) may be written as $r(x', x) = \phi(x')p(x', x)$ (Oxenius 1986), where $\phi(x) = (a/\pi)/(x^2 + a^2)$ is the normalized absorption coefficient and

$$p(x', x) = \frac{a_3}{a} \frac{2a_2/\pi}{(x - x')^2 + 4a_2^2} + \frac{a_2}{a} \phi(x). \quad (1)$$

Here $a_2 = A_{21}/(4\pi\Delta\nu_D)$ and $a_3 = (A_{31} + A_{32})/(4\pi\Delta\nu_D)$ are Voigt parameters for the lower and the upper level. Thermal velocity effects in the wings are negligible and will be ignored here. This implies that the frequency redistribution function in the wings is the same for the atom and the fluid frame. The redistribution function may be essentially simplified to reduce the number of scattering in the Monte Carlo computations preserving good precision. Since multiple local scattering in the Doppler core ($|x| < x_c \approx 3$) eventually ends up with the photon re-emitted in the wings, the scatterings in the Doppler core may be omitted by adopting the function $p(x', x)$ equal to zero in the core $|x| < x_c$. After the re-normalization this function is labeled $P(x', x)$. For instance, the function $\phi(x)$ in the second term of Eq.(1) transforms into $\psi_2(x) = 0.5x_c/x^2$ for $|x| > x_c$ and $\psi_2(x) = 0$ otherwise. Results are not sensitive to the choice of the core width and $x_c = 3$ is assumed.

The $\text{H}\alpha$ photon history is simulated as follows.

The photon is launched with the distribution function $\psi_2(x)$. When propagating it experiences a redshift in the co-moving frame until it randomly scatters or escapes. If scattered, the frequency of the re-emitted photon is randomly chosen according to the modified distribution function $P(x', x)$. The process continues until the photon escapes.

To demonstrate the role of H α damping wings in SN II-P let us consider a freely expanding envelope ($v = r/t$, v being the velocity at the radius r at the expansion time t) with a homogeneous line-emitting core ($v \leq v_1$) and a scattering halo ($v_1 < v < v_2$). The Sobolev optical depth of the halo decreases outward as $\tau = \tau_2(1 - v/v_2)$. The core, optically thin in the continuum, may emit a continuum radiation from homogeneously distributed sources. The velocity and the optical depth in the core (subscript 1) and in the halo (subscript 2), respectively, are given in Table 1.

The homogeneous core with the low optical depth in the model M1 produces a parabolic profile (Fig. 1a) expected for the Sobolev approximation. When the optical depth is high (models M2 and M3) the extended wings emerge, while the line core becomes broader and gets redshifted. All the effects are caused by the radiation transfer in the damping wings. Note, that in the case of the Sobolev approximation the models M2 and M3 would have the same parabolic profile as that of the model M1. A conspicuous kink at the blue slope in the model M3 is caused by a self-absorption due to non-local scattering. The models M4 and M5 show how the models M1 and M3 are changed when a scattering halo and a continuum core are present (Fig. 1b). The model M5 gives a realistic impression of damping wings effects in H α at the early nebular epoch of SN II-P.

How would the inhomogeneity of the hydrogen distribution in the mixed core change these results? Generally, the optical depth in the damping wing depends not only on the local concentration of absorbers, but also on its filling factor (f), and, in lesser degree, both on the size of inhomogeneities, and on their topological properties. In the limit of small scale inhomogeneities, when the mean free path length in the far wing exceeds a typical size of the inhomogeneity, the optical depth in the wing may be reduced to a simple form $\Delta\tau = (a\tau_1/x^2)f|\Delta x|$, where τ_1 is the Sobolev optical depth and $\Delta x = (dx/dl)\Delta l$ is the frequency shift in comoving frame at the length interval Δl . Under this approximation the H α profile from the inhomogeneous core is the same as that from the

homogeneous core with the "effective optical depth" $\tau_{1,\text{eff}} = f\tau_1$. The analysis of the H α damping wings thus permits us to estimate the H α effective optical depth in the mixed core, or, equivalently, fn_2 (n_2 being the population of the second hydrogen level). It is noteworthy that the derived value of fn_2 is independent of the adopted distance of a supernova.

3. Identification of H α damping wings effects in SN 1997D

The spectra of the type II-P supernova SN 1997D with a low expansion velocity have been obtained at the early ($t \approx 150$ d) and the late ($t \approx 300$ d) nebular epoch by Turatto et al. (1998). The nebular spectrum on day 300 was reproduced in the model of a spherically symmetric mixed core with the total ejecta mass of $6 M_\odot$ and the kinetic energy of 10^{50} erg (Chugai & Utrobin 1999). However, it was stressed there that H α on day 150 shows a significant redshift in a disparity with a spherically symmetric model. Note, that the asphericity of the ^{56}Ni distribution might produce the H α asymmetry on day 150 likewise it was in SN 1987A. However, this reason for SN 1997D is discarded by the absence of H α asymmetry on day 300. We will see below that damping wings effects may resolve the revealed controversy.

The assumed envelope model is similar to that of the Section 2, i.e., it consists of a line-emitting homogeneous core and a scattering halo. For models considered here the core velocity is $v_1 = 650 \text{ km s}^{-1}$ and the outer velocity of the scattering halo is $v_2 = 2000 \text{ km s}^{-1}$; the latter is consistent with the steep density drop in the range $v > 1500 \text{ km s}^{-1}$ for the hydrodynamical model of SN 1997D (Chugai & Utrobin 1999). The Sobolev optical depth in the halo is assumed to decrease outward as $\tau_2(1 - v/v_2)$ with $\tau_2 = 10$. An additional factor implemented into the model is the Thomson scattering, although it is of minor importance. The corresponding optical depth (τ_T) of the mixed core, estimated from the H α luminosity (distance $D = 13.43 \text{ Mpc}$) using data by Turatto et al. (1998), is 0.16 on day 150 and 0.08 on day 300. Below, I adopt $\tau_T = 0.1$ for $t = 150$ d and $\tau_T = 0.05$ for $t = 300$ d to roughly take into account that the hydrogen filling factor in the mixed core is essentially less than unity (Chugai & Utrobin 1999).

In the late time spectrum on day 300 the model without damping wings is not very much different to the observed profile (Fig. 2). It implies that

the damping wings at this epoch are not significant, although, the model with the damping wings and $\tau_{1,\text{eff}} = 5 \times 10^3$ fits the observed profile better. On day 150 the model without damping wings is strikingly dissimilar to the observed profile: the latter is broader and shows both significant redshift and red wing. The model with damping wings included and $\tau_{1,\text{eff}} = 5 \times 10^4$ turns out to be successful in the description of the observed profile. Note, that with the core velocity set by the late time profile, the primary fitting parameter is the effective optical depth in the mixed core.

The found effective optical depth value being combined with the Sobolev optical depth may be used to derive the hydrogen filling factor in the mixed core. To estimate the Sobolev optical depth I adopt $0.002 M_{\odot}$ of ^{56}Ni (Turatto et al. 1998) in the mixed core ($v \leq 650 \text{ km s}^{-1}$). The density $\rho \approx 5 \times 10^{-13} \text{ g cm}^{-3}$ is adopted on day 150 following the model of SN 1997D (Chugai & Utrobin 1999). The non-thermal excitation of hydrogen may be calculated assuming that all the energy of gamma-rays from the radioactive decay of ^{56}Co is uniformly deposited in the mixed core, which is a sound approximation at the early nebular epoch when the mean free path for gamma-rays is small. The energy deposited in H-rich matter is spent (apart from Coulomb heating), eventually, on the excitation of the second level of hydrogen. With the depopulation rate controlled by the two-photon decay and the collisional de-excitation I find $n_2 \approx 1.3 \times 10^4 \text{ cm}^{-3}$ on day 150, which leads to the Sobolev optical depth of $\approx 1.7 \times 10^5$. The latter being combined with the effective optical depth ($\tau_{1,\text{eff}} = 5 \times 10^4$) results in the hydrogen filling factor of $f \approx 0.3$. The latter value is quite realistic, although it is a factor of 1.5 larger than the estimate from the nebular model on day 300 (Chugai & Utrobin 1999). The difference is not dramatic taking into account possible uncertainties of both models. The factor of ten lower value of the effective optical depth in H α on day 300 compared to that on day 150 is consistent with the decrease of the Sobolev optical depth in H α expected for the mechanism of the non-thermal excitation (e.g., Xu et al. 1992).

Although describing an inhomogeneity of the excited hydrogen in the mixed core in terms of the filling factor seems sensible, a possibility exists that between the mixed core and unmixed hydrogen envelope there is a transition layer of strongly excited hydrogen with the filling factor of unity. To estimate qualitatively

effect of this component I introduced in the model on day 150 an additional spherical layer in the velocity range $650\text{--}700 \text{ km s}^{-1}$ with filling factor of unity, negligibly small net emission, and the Sobolev optical depth being equal to the effective optical depth of the mixed core. Such a choice of optical depth suggests factor of three lower hydrogen excitation in the transition layer than in the mixed core. The new model is found to produce the same H α profile as in the old model provided the effective optical depth of the mixed core is of $\tau_{1,\text{eff}} = 4 \times 10^4$, i.e., 20% lower compared to the old model. This implies that the value of the H α effective optical depth found from the profile modelling is quite robust to reasonable editing the geometry of the distribution of the excited hydrogen in the mixed core.

Summing up, the H α damping wings effects provide a natural explanation for the dramatic discrepancy between the model based on the Sobolev approximation and the observed profile in SN 1997D on day 150. This conclusion is strengthened by the absence of a reasonable alternative.

4. Summary and Discussion

At the early nebular epoch of SN II-P the H α emission should exhibit observational signatures of damping wings. Although, the damping wings were never considered before as relevant for supernova optical spectra, the claimed effects are robust and may be easily identified. We see damping wings effects in SN 1997D spectrum, where they are responsible for the redshift, large width and extended red wing of H α on day 150. The detection of H α damping wings effects in SN II-P provides a direct estimate of the H α effective optical depth (i.e. the product of the Sobolev optical depth and the hydrogen filling factor) in a distance independent way. We thus obtain a reliable test for nebular models of SN II-P. On the other hand, with a confident nebular model in hand, we may be able to measure the hydrogen filling factor in the mixed core. The price for this knowledge is the abandoning the Sobolev approximation and the need for the full radiation transfer treatment of the H α radiation.

Needless to say that the simple model of the H α profile used above for SN 1997D admits some improvements. For instance, one may take the radial dependence of hydrogen excitation and filling factor in the mixed core into account. Another modifica-

tion, might be the inclusion of the absorption of $H\alpha$ quanta in the Paschen continuum. This may be done if the radiation transfer and the hydrogen excitation are calculated simultaneously. More detailed description of the hydrogen inhomogeneities is also welcome, although the expected change of the value of the effective optical depth would be within 20%.

To recover the damping wings in other SN II-P it is necessary to use at least two nebular spectra: at the early epoch, (around day 150) and at the late epoch, but before the dust formation, (e.g., between 300 d and 400 d). The early nebular epoch is most appropriate to extract the information about damping wings, while the late time nebular spectrum provides a template to set the core velocity and to secure results from a confusing effects of asymmetric ^{56}Ni distribution. Notably, it is ^{56}Ni asymmetry that prevent us from using a simple symmetric model to study $H\alpha$ damping wings effects in SN 1987A.

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REFERENCES

- Chugai, N.N. 1980, *Sov. Astron. Lett.* 6, 91
- Chugai, N.N. and Utrobin, V.P. 1999, *A&A*, in press
- De Kool, M., Li, H., and McCray, R. 1998, *ApJ*, 503, 857
- Kozma, C. and Fransson, C. 1998, *ApJ*, 497, 431
- Oxenius, J. 1986. *Kinetic theory of particles and photons*, Berlin: Springer-Verlag, 1986, 309
- Turatto, M., Mazzali, P., Young, T.R. et al. 1998, *ApJ*, 498, L129
- Xu, Y., McCray, R., Oliva, E., and Randich, S. 1992, *ApJ*, 386, 181

Table 1: Parameters of demonstration models

Model	v_1 (km s ⁻¹)	$\tau_1 \times 10^{-4}$	v_2 (km s ⁻¹)	τ_2
M1	2000	0.001	2000	0
M2	2000	2	2000	0
M3	2000	5	2000	0
M4	2000	0.001	4000	10
M5	2000	5	4000	10

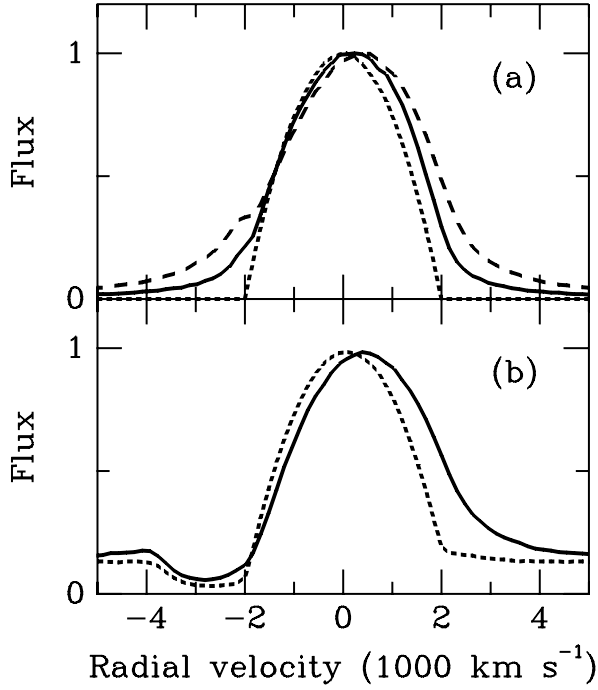


Fig. 1.— Effects of H α damping wings expected for SN II-P. The panel (a) displays the case without continua and a scattering halo. The dotted line is the Sobolev approximation (model M1), while the solid line (model M2) and the dashed line (model M3) show effects of damping wings. The panel (b) displays the case with the continua and the scattering halo. The dotted line is the Sobolev approximation (model M4), while the solid line shows the model M5 with damping wings.

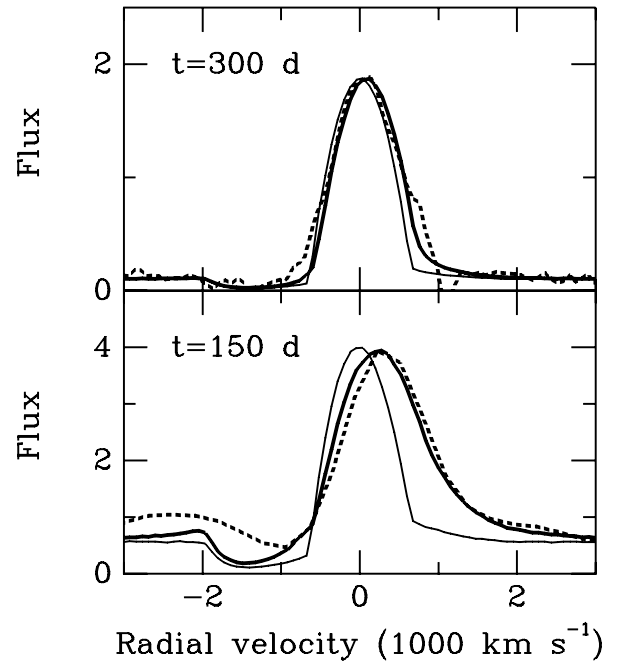


Fig. 2.— Calculated and observed H α in SN 1997D on days 150 and 300. The dotted line is the observed spectrum; the Sobolev approximation is shown by the thin solid line, while the thick solid line shows the model with damping wings.